TRAVELING-WAVE TUBE AMPLIFIER CHARACTERISTICS STUDY FOR STOCHASTIC BEAM COOLING EXPERIMENTS

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Summary

The characteristics of continuous-wave wideband traveling-wave tube amplifiers have been experimentally investigated over a frequency range of 1.5 to 4.5 GHz. We present measurements of characteristics important for stochastic beam cooling systems that are generally not available from manufacturers' data sheets. The amplifiers measured include models 1177 HO1 and 1277 HO1 having output power capabilities of 10 to 20 W, respectively, at frequencies of 2 to 4 GHz. The power transfer characteristics, the phase-shift characteristics as functions of frequency and the input power level, the voltage standing-wave ratio, harmonics and intermodulation products content were accurately measured and are discussed. Also several approaches are discussed for the reduction of harmonics and intermodulation products.

Introduction

An effort is underway at the Fermi National Accelerator Laboratory and Lawrence Berkeley Laboratory to design the Antiproton Source which will make it possible to produce proton-antiproton collisions at energies near 2 TeV in the center of mass. The Antiproton source will be capable of accumulating $4 \times 10^{11}$ antiprotons in four hours when a wideband feedback system for stochastic beam cooling is used. This method has been effectively used for the gradual reduction of betatron oscillations and longitudinal momentum spread of a coasting particle beam.

The Antiproton Source program requires the development of two types of wideband amplifier systems, one type capable of operating at power levels of several hundred watts and the other at power levels of several thousand watts in the frequency bandwidths covering 1-2 GHz and 2-4 GHz. Since the pickup electrodes generate very small signal power levels from the antiproton beam amplifier systems should have a gain in excess of 90 dB and 150 dB, and noise figures as low as possible.

Our previous experiments indicate that new amplifier systems should be designed which meet the above requirements for fast cooling of betatron oscillations and longitudinal momentum spread. Initially Power Gallium-Arsenide Field-Effect Transistors and Helix Traveling-Wave Tubes (TWT) were considered as potential devices for the amplifier driver and output stages. Detailed device characteristics studies have shown that at the present time only helix-type TWT's are capable of meeting the technical objectives of output power level, bandwidth, phase-shift variations, and reliability. Because of the TWT's excellent gain bandwidth and output power capabilities, the device can significantly contribute to the development of stochastic cooling systems. However, device characteristics must be carefully studied, particularly with respect to generation of harmonics and intermodulation products during amplification process. Harmonics and intermodulation products are generated as a result of the inherent nonlinearity of the beam-helix wave interaction process in TWT's when multiple input signals (or noise) are applied. The generation of such harmonics and intermodulation products in the amplifier system may cause the stochastic heating rather than cooling of antiproton beam.

Dynamic Range and Power Transfer Characteristics Measurement

The dynamic range measurement of the TWT amplifier shows performance characteristics such as linearity and gain. Approximately 100 mW of signal power was required to drive the TWT amplifier under test to provide full power output and operate beyond the saturation.

The dynamic range measurement of the TWT amplifier as a function of the input power level with the input signal frequency as a parameter. Results of the measurements show that the amplifier has its 1 dB attenuation point at input power levels of 40, 42, and 45 dBm for frequencies of 3, 2, and 4 GHz, respectively. Saturation points were 45, 42, and 45 dBm for input signal frequencies of 3, 2, and 4 GHz. The output power variation across the specified bandwidth was approximately 12 dB. As the input power approached 0 dBm, the output power curve showed a marked saturation. The linear operating range of the TWT amplifier was definitely below 0 dBm of input power over the 1.5 to 4.5 GHz range. The output noise power level of the TWT was -55 dBm. For this measurement the spectrum analyzer bandwidth was 300 KHz.

Phase-Shift Characteristics Measurement

Figure 2 is a set of curves showing the phase-shift of the TWT amplifier output signal as a function of frequency at various input power levels. The measuring system phase-shift had been subtracted and this figure presents the true phase-shift of the TWT amplifier output with zero phase set at 2.5 GHz and -10 dBm input power level. The amount of phase-shift over a bandwidth of 2-4 GHz at 0 dBm input power level was approximately 21°. At input power level of -10 dBm, the phase-shift was approximately 1°.

Figure 3 is the phase-shift of the TWT amplifier as a function of input power level with input signal frequency as parameter. The 2, 3, and 4 GHz curves are all normalized with respect to each other through a zero phase set point fixed at 2.5 GHz and -10 dBm input power level. For the input power dynamic range from 0 to -20 dBm, the phase-shift as a function of the input power level varies 2, 7 and 45° for the input signal frequencies of 4, 2 and 3 GHz, respectively.

Dynamic Range and Intermodulation Products Measurement

The dynamic range and intermodulation product measurement of the TWT amplifier shows such performance characteristics as the linearity, gain, harmonic interference, and the intermodulation performance which can be expected from the amplifier at fundamental frequencies. As a result of the inherent nonlinearity of the electron beam-helix wave interaction process, harmonics and intermodulation products are formed when multiple input signals (or noise) are applied which reduce the available power levels of the fundamental signals. Distortion and nonlinear effects are caused by electron bunching, velocity modulation, and electron over-taking in the beam. Generally, when two input signals with frequencies $f_1$ and $f_2$ are applied to the TWT amplifier the frequency of the intermodulation signal is $mf_1 + nf_2$, where $m$ and $n$ are positive integers. One of the integers may take the value.
With respect to those commonly available. The design forward techniques. Optimization of the TWT operating conditions could reduce the device distortion. Furthermore, the possibility should be explored of developing a special TWT having improved amplitude linearity. The design of standard TWT's by manufacturing industry has, in most cases, emphasized power efficiency, output power levels, bandwidth, gain, size, reliability rather than amplitude linearity. For stochastic beam cooling systems, the emphasis should be on amplitude linearity, bandwidth and reliability, sacrificing to some extent power efficiency and gain. The amplitude linearization of the TWT would also result in an improvement in phase linearity.

The required output power level of the octave-bandwidth amplifier for the stochastic cooling systems can be obtained by either a large number of low power CW Traveling-Wave Tubes (200 W saturated power level) or a relatively small number of medium power TWT's (1.5 kW saturated power). The use of low power TWT's rather than medium power tubes has the following advantages: higher reliability, availability of the tubes from at least three major manufacturers, willingness of one manufacturer to redesign the TWT to reduce harmonic and intermodulation product output, and a better output power-to-price ratio ($100/W for 200 W tube versus $220/W for 1.5 kW tube). The octave bandwidth CW medium power TWT's are available only from one major manufacturer which presently is not willing to make any tube modification for reduced harmonic and intermodulation products output. Mean-Time-Between-Failure (MTBF) of 200 W TWT's is, on average, less than 20,000 hours, and the 1.5 kW TWT's has MTBF of approximately 3,000-5,000 hours. With a high redundancy design, the reliability of a 200 W TWT system can be significantly higher than that of a 1.5 kW TWT system.

Concerning the configuration of high power TWT's in the output stage, the TWT's can be reliably used only as single units in the octave bandwidth. Although, the operation of several TWT's in parallel configuration is possible for obtaining higher power levels, it requires a complex protection circuitry, careful phase and amplitude matching and precise maintenance of the matching conditions over the operational lifetime of the output stage. So far, parallel configuration of TWT's has been used exclusively in military electronic counter measure systems, in the octave bandwidth, purely to increase the output power level. It cannot be used to reduce the harmonics and intermodulation product content due to a complex interaction of beam-helix wave in TWT's.

In satellite communication applications where requirements are more stringent in terms of amplitude, phase linearity and gain stability (to some extent, similar to stochastic cooling system requirements), the parallel combination of two TWT's has been used only for relatively narrow (8%) bandwidths. Specifically, a satellite earth terminal was developed which is capable of delivering 1 kW CW in a bandwidth extending from 5.9 GHz to 6.4 GHz (C-Band) by combining two 500 W TWT's and using an in-phase power combiner. At X-Band frequencies the satellite communication systems successfully use only 5% bandwidths. The relatively narrow operational bandwidths in both cases was essentially determined by the accuracy of phase tracking in all precision components used in the system, such as the input in-phase power splitters, attenuators, phase shifters, the TWT's and the output in-phase power combiners.

Single TWT configuration in the output stage would eliminate the precise amplitude and phase matching requirements over the required large bandwidth and output signal dynamic range. Furthermore, such a configuration will allow freedom in optimizing the operating conditions of each tube in the system, as well as the application of amplitude and phase predistorting networks and feedforward techniques.
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References


